0.8 – 5.0 keV X-ray Emission from the PFRC-2 Plasma

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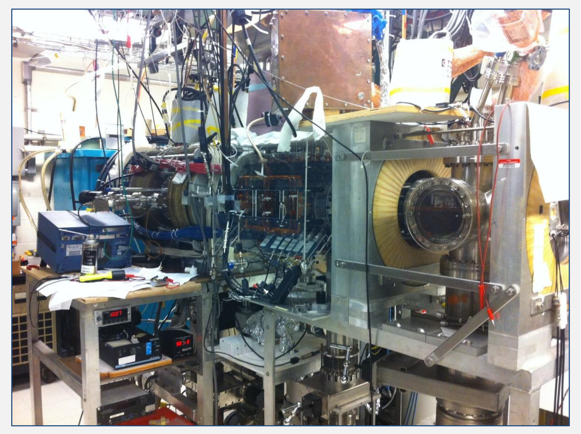
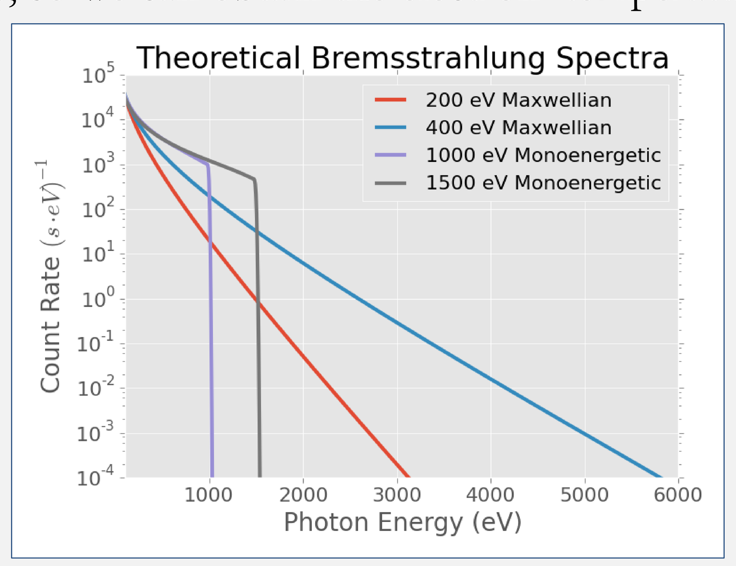
The PFRC-2

The Princeton Field-Reversed Configuration is an experiment investigating odd-parity rotating-magnetic-field (RMF_o) driven FRCs. FRCs are attractive for use in fusion reactors because of their natural high beta and their simple geometry. RMF_o is predicted to be able to form and heat stable FRCs to thermonuclear conditions. If this is indeed the case, RMF_o-driven FRCs could form the basis for small, efficient fusion reactors for electrical energy generation and propulsion.



Bremsstrahlung

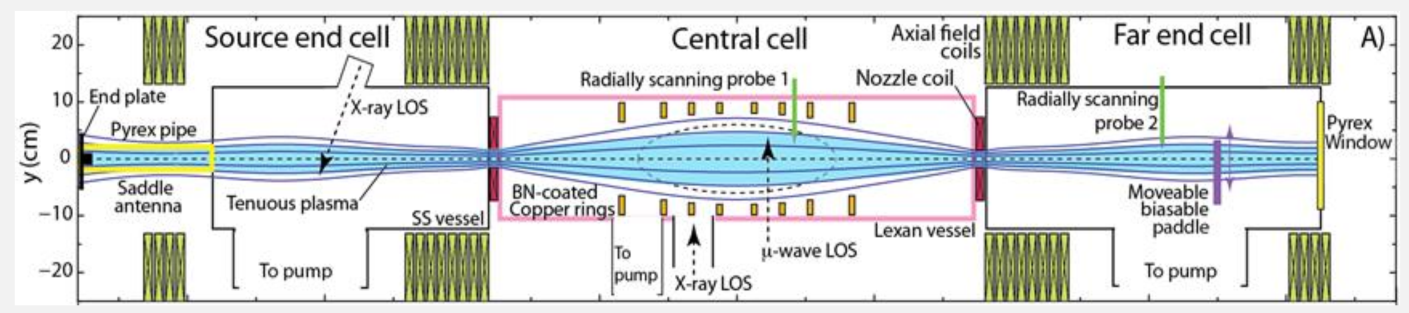
Bremsstrahlung is radiation produced when electrons undergo acceleration during collisions with ions or neutrals. We can learn a lot about a plasma's electron distribution by observing it's bremsstrahlung x-ray emission. From the electron distribution, we can learn about the relevant heating and confinement physics. Shown to the right are calculated x-ray spectra for Maxwellian and monoenergetic electron distributions. For a Maxwellian distribution, the high-energy spectrum is dominated by a $\exp(\frac{-h\nu}{kT_E})$ dependence, so we can obtain the electron temperature from the slope of the logarithm of the spectrum. An experimentally observed spectrum would be blurred by the finite resolution of the detector and decreased at low energies according to the transmission efficiency of the detector's beryllium window.



Detector System

We used an Amptek XRC-100 Si-PIN diode x-ray detector. When a photon strikes the diode in the detector, it generates electron-hole pairs proportional to the energy of the photon. By applying a bias voltage, this current can be collected, amplified, and shaped so the energy spectrum of incoming photons can be determined accurately with a high throughput rate. The detector was calibrated using an Fe-55 source. For shaping, we used a ~12 µs long triangular pulse. Given the observed count rates of <1000 s^{-1} and the built-in rejection circuitry, pulse pileup should not be an issue.

Experimental Setup

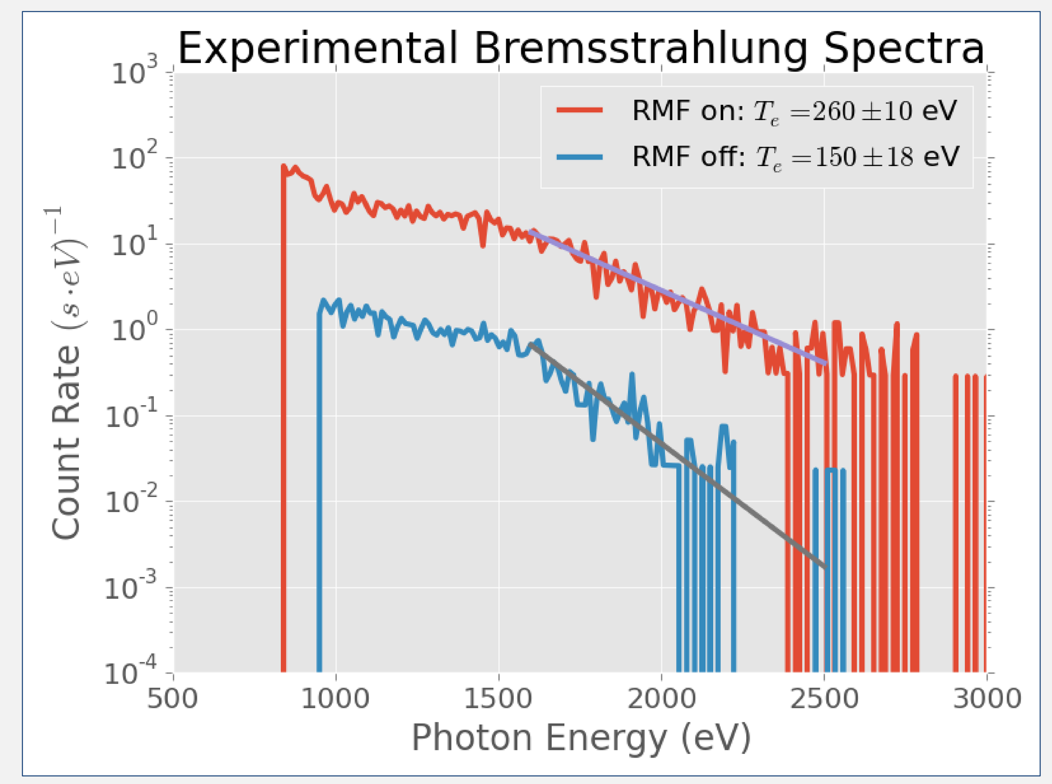


Typical Operating Conditions	
RMF power	5-20 kW
Pulse length	4-50 ms
Duty cycle	0.5 %
Source Power	20-300 W
Background field	35-100 G
Nozzle field	1800 G
Neutral pressure	1.0 mT
Electron density	10^{12} cm^{-3}

A schematic of the PFRC-2 is shown above. A double-saddle antenna creates a cold, tenuous seed plasma which flows along the magnetic field lines to the central cell. In the central cell, the RMF antennas (not shown) drive a strong, azimuthal current in the seed plasma that causes further ionization and field reversal. The superconducting flux-conserving rings prevent the radial expansion of the plasma. The x-ray detector looks radially in at the plasma, slightly off-center towards the source.

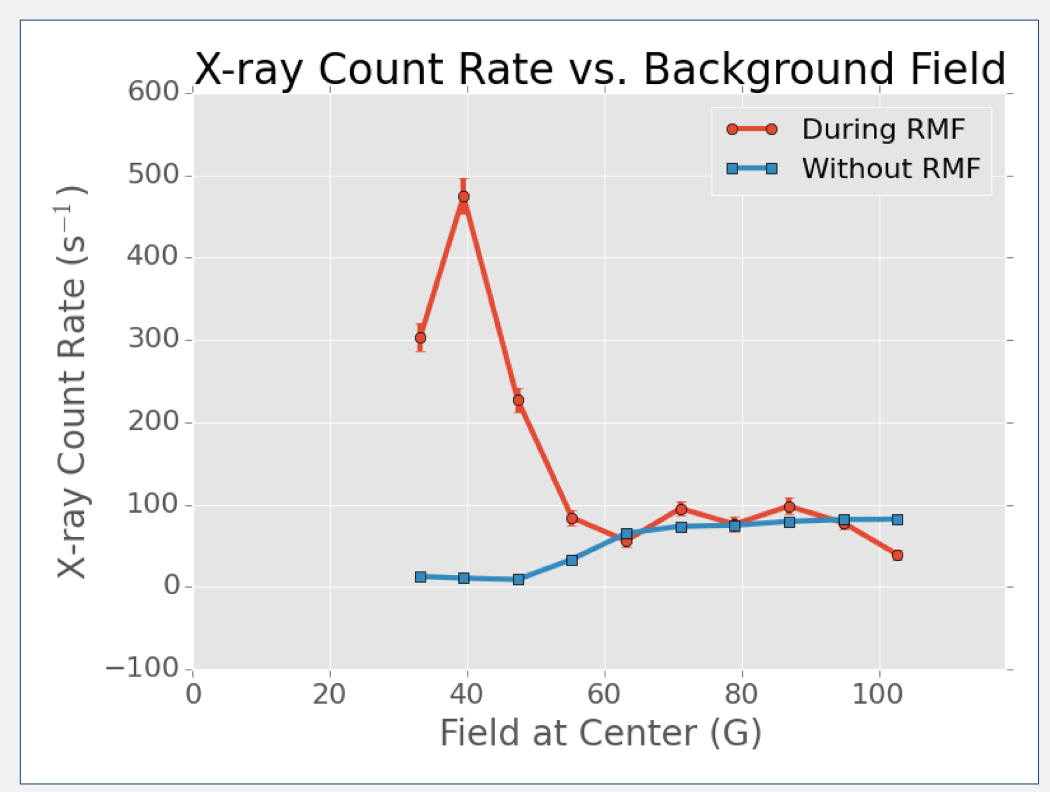
Experimental Spectra

Shown above is a comparison of the x-ray spectrum seen during an RMF pulse and the spectrum from the seed plasma. The shape of the spectra are similar, but there are roughly an order of magnitude more electrons during the RMF pulse.. In addition, the electron temperature from the linear fit is significantly hotter. This suggests that there is significant heating and confinement of electrons during the RMF pulse. Both spectra are relatively flat at low energies which may be due to a beam-like population of secondary electrons from the source.

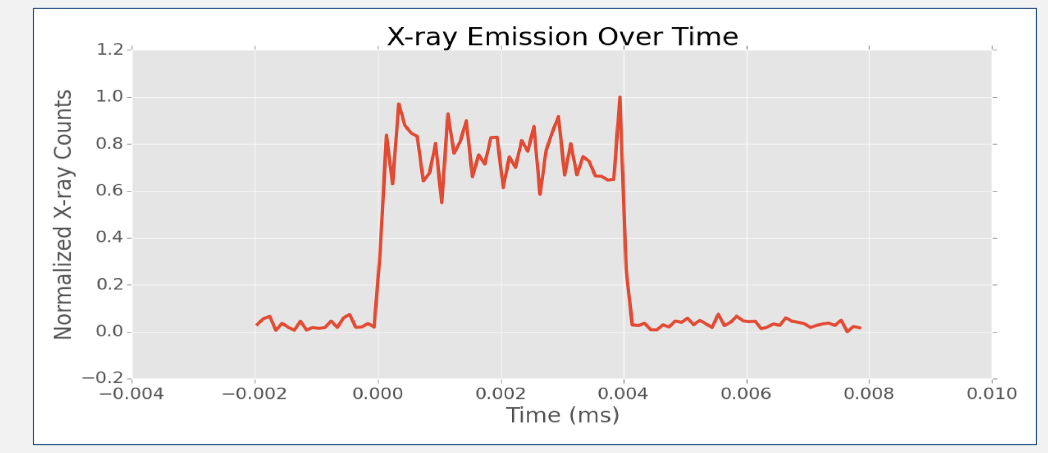


X-ray Emission vs. Background Field

There is a strong peak in x-ray emission with the background field around 40 G at the center of the machine. Emission during the RMF sharply decays as the field increases up to 50 G, after which it remains roughly constant. At around 75 G, significant low-frequency oscillations show up on interferometry readings and visible light measurements. Interestingly, x-ray emission when the RMF is off has an opposite relationship with the background field, sharply increasing between 40 and 60 G. At over 100 G, actually fewer x-rays are seen when the RMF is on than when it is off, indicating that effective confinement and heating is not occurring.

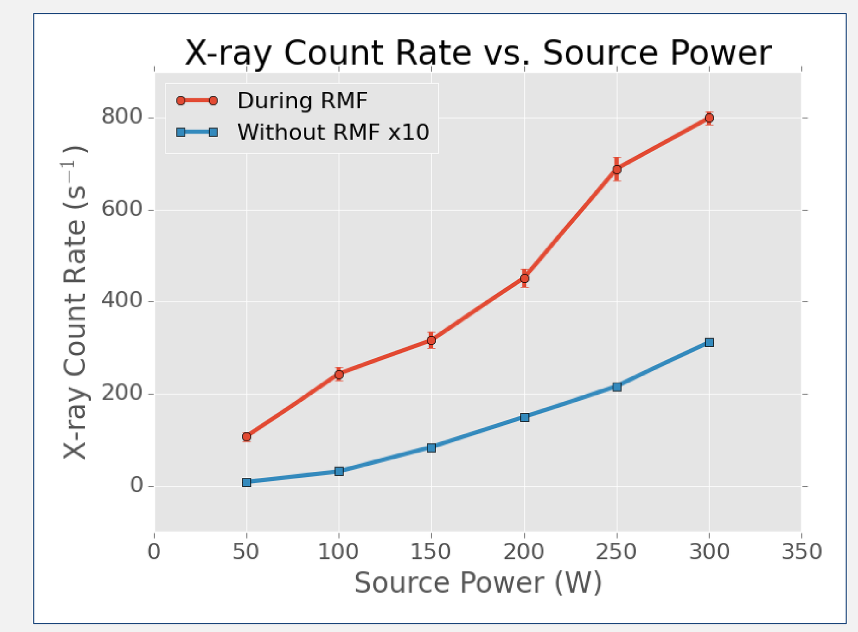


X-ray Emission Over Time



The plot above is a histogram of the number of x-rays detected summed over several thousand 4 ms RMF pulses. X-ray emission is uniform throughout the duration of the pulse and rises and decays within 100 µs.

X-ray Emission vs. Source Power



X-ray emission during the RMF pulse steadily and significantly increases as the power for the seed plasma antenna increases. The most significant change in the seed plasma as the source power increases is an increase in the number of very energetic secondary electrons in the bulk plasma, seen here as an increase in x-ray emission without RMF. Perhaps this means that these energetic seed electrons significantly improve the coupling of the RMF to the plasma, but further experimental and theoretical investigation is required.

Summary

- RMF_o forms stable, hot (>200 eV) plasmas when background field is low. When the field is high, the RMF does not significantly change the population of fast electrons from the seed plasma.
- Increasing the power of the seed plasma antenna enhances x-ray emission during the RMF pulse, likely due to the increase in the number of fast electrons in the seed plasma.
- In order to move towards fusion-relevant regimes, the PFRC-2 must be operated at much higher fields. Determining the cause of the loss of confinement/heating at high fields is thus a major near-term goal.
- In the next several months, the RMF power will be increased from 20 to 200 kW. It is unknown what effect this will have on the behavior described here.